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REVIEW ARTICLE

Reconciliation of research on forest carbon sequestration and water conservation

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Abstract Carbon sequestration and water conservation are two of the key ecosystem services that forests provide for societal need to address environmental issues. Optimization of the dual services is the ultimate goal in forest management for mitigating global climate change and safeguarding terrestrial water balance. However, there are some tradeoffs between gain in forest productivity and ecosystem water balance. We conducted literature review based on published articles for learned knowledge on forest carbon fixation and hydrological regulations. Some knowledge gaps and research needs are identified by examining the inter-connections between forest carbon sequestration and water conservation. Past researches have helped gain basic understanding of the mechanisms and controls of forest carbon fixation and hydrological regulations as two separate issues. Tools and approaches are well established for quantifying and monitoring forest carbon and hydrological issues, operating at different spatial and temporal scales. There are knowledge gaps on how to design afforestation schemes facilitating enhanced ecosystem services in forest carbon sequestration and water conservation. For the top-down planning of afforestation in regions where water availability is anticipated to be problematic, the questions of how much and where to plant for given land availability, known environmental implications, and sustained regional development and livelihood need to be addressed. For local management considerations, the questions of what and how to plant prevail. Efforts are needed in joint studies of forest carbon sequestration and water conservation functionalities, specifically in relation to establishment and management of planted forests aiming for delivering regulatory ecosystem services in carbon sequestration, water conservation and other social values. We propose an integrated framework with dual consideration of carbon sequestration and water conservation in forest management for future research pursue.

Keywords Carbon balance · Ecosystem services · Forest management · Hydrological processes · Tradeoff

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Introduction

Forests are well recognized for their role in provisioning of ecosystem services (Costanza et al. 1997), of which carbon sequestration and water conservation are of key considerations in contemporary forest management due to concerns on global climate change and water resources safety. While expansion of forests is favored for enhanced terrestrial carbon sequestration and increased overall ecosystem services globally, establishment of large-scale plantation forests involves tradeoffs for decreased local water availability (Jackson et al. 2005; Doelman et al. 2020) and reduced streamflow (Trabucco et al. 2008; Zhang et al. 2017b). Such tradeoffs are of particular concern in regions with water scarcity and periodic drought problems (Malmer et al. 2010; Matyas and Sun 2014; Schwärzel et al. 2020). However, in regions where water is non-limiting, forests play a regulatory role on local water cycle by temporarily retaining rainwater through either improved water infiltration in soil or increased water storage in litter layer, thereby avoiding immediate runoff water losses (Wu et al. 2020).

In views of the natural sustainability issues and societal expectations, planning and management of plantation forests require sound knowledge of the technical measures gaining optimized socioeconomic benefits while minimizing or facilitating environmental impacts. In traditional forestry, wood harvesting, tree regeneration and forest protection are three core objectives of forest management. Behind various forest management activities in support of those objectives are active research efforts targeting the delivery of desirable forest products (Fig. 1). Realizations of the vital roles of forests in environmental regulations and eco-safety have promoted the development and management of plantation forests for non-timber products and/or services in modern forestry (Haakana et al. 2020; Temperli et al. 2020). Increased carbon sequestration capability and effective water conservation benefits are two of the key services highly regarded for forest ecosystems (Li et al. 2019). Over the decades, numerous studies have been conducted to quantify the capacity and controls of forest carbon sequestration, and to determine the regulatory roles of forests in local and regional water cycles.

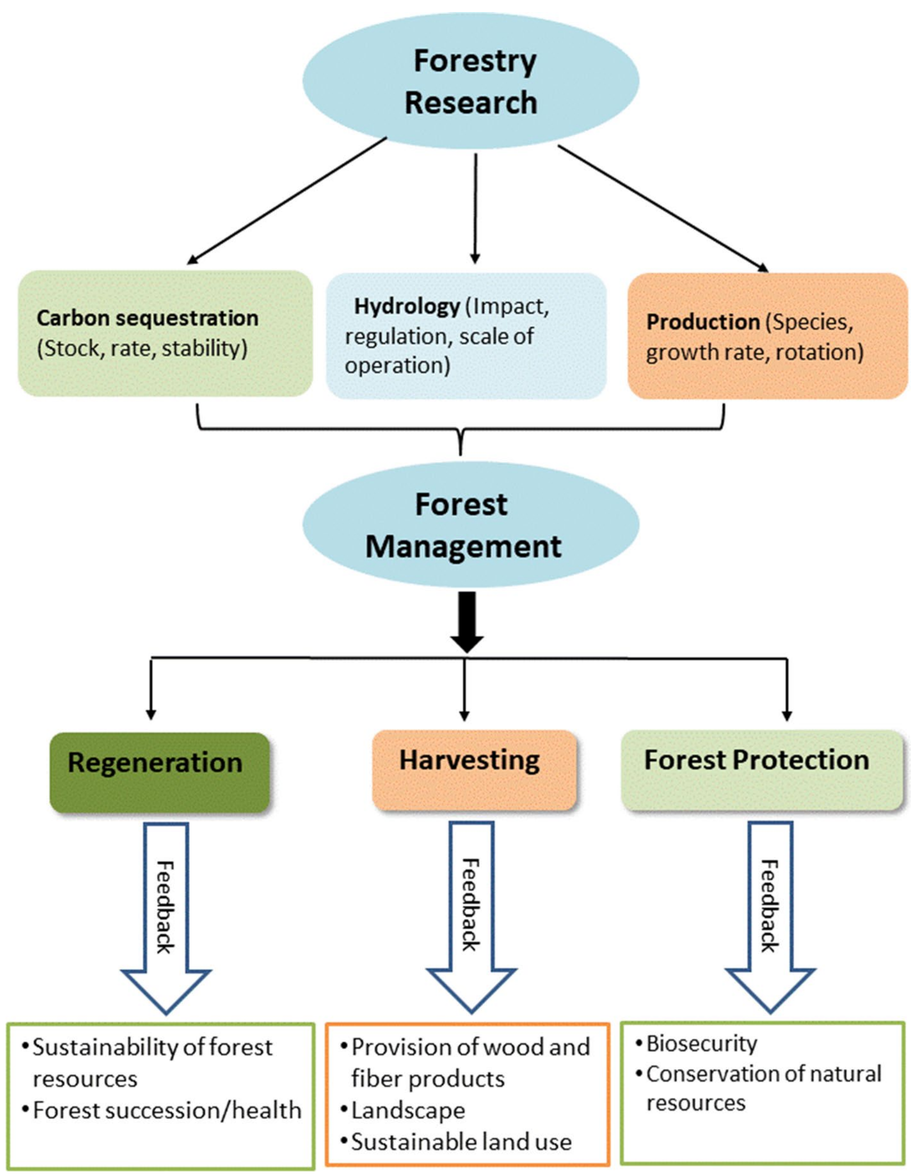

Fig. 1 Linkage of traditional forestry research to forest management

Search of Web of Science for papers published in 1985–2020 using the key words "forest + carbon" yielded 84,752 results; the number of results reached 101,633 under the search for "forest + water use", and 13,413 under "forest + hydrology". Search for "forest + carbon + water use" produced 26,823 outcomes, and 2556 for "forest + carbon + hydrology".

This review examines some of the learned knowledge and current development in forest carbon fixation research and studies of forest hydrological processes. Our aims are to identify key knowledge gaps in understanding the interconnections between forest carbon sequestration and water conservation, and to develop a framework for future forest research and management with dual consideration of carbon sequestration and water conservation.

Forest carbon sequestration

Forest plants fix and store carbon in biomass, woody debris, litter and soils. Earlier research on forest carbon stocks has been predominantly concerned with development of tools and approaches in quantifying forest carbon stocks and their partitioning in various carbon pools, as well as in identifying the spatiotemporal variations in forest carbon fixation and controlling factors. Traditional estimations of forest carbon stock and its changes include harvesting and modeling methods. Direct harvesting of trees involves measurements of different tree components, such as trunk, leaves, branches, and roots (Zhou et al. 2019; Sun and Liu 2020). Soils were also sampled to provide full accounting of forest ecosystem carbon stock (Tang et al. 2018). Although the traditional approach provides the most accurate estimates of carbon stock, it is generally costly, labor intensive, time consuming, and sometimes impossible due to poor accessibility. A less intensive approach is to calculate forest carbon stock using allometric equations. Allometric equations for biomass estimation are developed by establishing a relationship between biomass and the various physical parameters of the trees such as the diameter at breast height, tree height, crown diameter, and tree species (Vashum and Jayakumar 2012). By incorporating forest inventory data and biomass prediction equations of different tree species, researchers are able to assess regional or national carbon stocks (Law et al. 2004). Forest carbon stock changes (fluxes) can also be quantified if repeated inventory data are available (e.g. Fang et al. 2001).

The development and applications of remote sensing products of vegetation and ecosystem process modelling, combined with site measurements and forest inventory data, have allowed cost-effective, large scale studies of forest carbon budgeting and underpinning the factors contributing to spatiotemporal dynamics of forest carbon stocks. The applications of remote sensing approach can be classified into two groups: one for assessing forest biomass carbon stock and the other for depicting forest carbon changes (fluxes). In the area of forest carbon stock assessment, many studies were conducted to build relationships between satellite-derived index with ground-based biological measurements, and then extrapolating the relationship spatially to obtain regional estimates. Satellite data for forest biomass carbon stock assessments are collected from passive (multispectral, hyper-spectral sensors) and active (light detection and ranging [LiDAR], and radio detection and ranging [radar] sensors) remote sensing techniques. Passive remote sensing relies on reflection signals of land surface from solar radiation, which is therefore operational at local to global scales (Timothy et al. 2016). Nonetheless, this approach is more sensitive to crown surface than below-canopy factors, rendering forest biomass less capable to be captured in dense forests as the reflected signals saturated (Tucker and Sellers 1986). Active remote sensing, on the other hand, retrieves signals emitted from airborne instruments for forest biomass reconstruction. Active remote sensing techniques are advantaged in providing forest structure information (e.g. tree height, crown area, and trunk size) regardless of the weather condition, which is the known challenge in passive remote sensing. Forest carbon fluxes are quantified using satellite-derived index as a pivotal driving factor. Light use efficiency model is the most typical tool for developing satellite-derived vegetation index, such as CASA, VPM, and GIO-PEM. It predicts net primary productivity (NPP) assuming directly proportional relationship between vegetation carbon uptake and the absorbed photosynthetically active radiation (APAR) (Medlyn 1998). Due to the simplicity of light use efficiency model, it can be easily extrapolated to regional and even global scales.

Despite the superiority in delineating macro-scale vegetation activity, remote sensing approach is limited to produce carbon fluxes and aboveground biomass carbon using simplified, empirical models. While in comparison, underground soil carbon stock and dynamics were less capable to be directly obtained from satellite observations. Integrating ground-based biological measurements, remote sensing data, and ecosystem modelling has proven an effective approach of quantifying regional forest carbon stocks and balances (Law et al. 2004).

Many factors affect the density and partitioning of carbon in forest stands. Continentally and globally, climate appears to the most important factor shaping the spatial patterns of forest carbon stocks (Pan et al. 2011; Zhou et al. 2019), and locally and regionally, the density and partitioning of forest carbon varies with tree species, forest structure and types, stand development, management, and soil conditions (Giardina and Ryan 2000; Law et al. 2004; Sun et al. 2004; Li et al. 2019). Marked differences can been found in forest carbon in relation to forest types, development, and site conditions regionally (Law et al. 2004) and at landscape-scale (Li et al. 2019), and between natural and planted forests (Yu et al. 2019). Natural and anthropogenic disturbances, accidental or intentional, are all detrimental to the stock and stability of forest carbon pools. While wood harvesting and fire cause instant removal of forest biomass carbon, chronical events such as insect outbreak and drought also lead to variable impacts on the fixation and cycling of forest carbon (Pregitzer and Euskirchen 2004). Harvest-related increases in decomposition affect the C budget over the entire harvest cycle (Noormets et al. 2015). Fire can have differential roles in affecting forest biomass carbon and soil carbon; it reduces biomass carbon by burning down the trees, and modifies carbon pools. The occurrence of black carbon produced by fire alters SOC composition in favor of enhanced recalcitrance. It is considered that, through proper ecosystem management and wood utilization, some forests have potential for enhanced carbon sequestration (Boisvenue et al. 2012; Lempriere et al. 2013). Recent studies also show that fast urbanization in China strongly increased forest soil carbon sequestration at urban center (Zhai et al. 2017; Lv et al. 2018), possibly owing to soil fungal-related carbon and soil carbon turnover rate (Wang et al. 2019b, 2020). Landscape-level configuration could improve forest ecosystem stability and favor tree growth and carbon sequestration (Zhang et al. 2017a, b; Yang et al. 2019; Zhao et al. 2016).

Recent studies of forest carbon sequestration have been oriented in uncovering the hidden box of carbon pools, i.e. soil carbon. In majority of the forest stands, only about a third of carbon are stored in living plants as biomass; the remaining two-thirds are in soils as SOC and litter (Law et al. 2004; Sun et al. 2004). Soil carbon retention and stability have emerged as of recent research interest (You et al. 2014; Wang et al. 2015, 2019a; Sun et al. 2019). Soil organic carbon storage and turnover are affected by climate, management, and disturbance, leading to spatial and temporal variations (Giardina and Ryan 2000; Schuur et al. 2001). The stability and long-term stores of soil organic carbon may be determined by chemical recalcitrance and physical protection of carbon compounds and complexing (Sollins et al. 1996; Wang et al. 2019a). Soil organic carbon is generally better preserved in humid soils and under low temperatures (Schuur et al. 2001; Sun et al. 2004, 2019). Returning farmland to larch forests has been shown to increase carbon in mineral soils at a rate of 100 g m^{-2} a^{-1} (Wang et al. 2011), which is a significant addition to carbon sequestration in aboveground biomass. Different species showed different capacities in its carbon sequestration, and soil nutrient utilization, indicating proper species could shape forest's carbon sink size in mineral soils, especially in the deep soil layers (Wang et al. 2014, 2017; Wu et al. 2019).

On the ecosystem service of forest carbon sequestration, research to date well supports the scaling up of forest carbon stock and fluxes from stand level to regional and global scales (Law et al. 2004; Pan et al. 2011; Zhou et al. 2019).

Forest water relations and hydrological processes

While expansion of planted forests is viewed as a favorable option for mitigating greenhouse gas emission and delivering multiple ecosystem services, there are increasing concerns on the potential risks of large-scale afforestation to regional water securities in drylands (Doelman et al. 2020; Schwärzel et al. 2020). Forests are known for their requirements of sufficient water supplies and roles in hydrological regulations. However, unlike carbon sequestration, the scale-dependent forest water relations and hydrological processes are less understood due to mostly technical difficulties in observational studies. Although the effects of forest cover change on water resources has been investigated at different scales using various methods, a consensus on the conclusion remains an open question due to enormous discrepancies between studies (Brown et al. 2007; Bosch and Hewlett 1982; Sun et al. 2006; Trabucco et al. 2008). Experimental observations at the watershed scale reflect a "bottom-up" approach in examining the role of forests in hydrological regulations. For small watersheds (< 1000 km^2) that have been intensively studied, a general agreement is that forest cover loss/gain increase/reduce annual runoff (Zhang et al. 2017b). While in comparison, large watersheds (> 1000 km^2) are more complex but much less examined due to data limitation and confounding factors (e.g. climate variability, urbanization, dam construction; Zhang et al. 2017b). Modeling using energy-based equations or water-balance simulations represents "top-down approach" (Zhou et al. 2015). Such models are designed with varied degrees of empiricism assuming ET is primarily controlled by available energy and water (Zhang et al. 2004; Sun et al. 2006; Trabucco et al. 2008). Recent studies highlighted watershed characteristics as a critical parameter in explaining the effects of land cover change on water resources (Zhou et al. 2015; Liu et al. 2016).

Despite the impact of reforestation or afforestation on water resources are still debated, it is generally recognized that trees can reduce runoff at the small catchment scale but it links to the increased precipitation and water availability at large scale (Ellison et al. 2012). It remains a question of great interest to know the footprint that a forest operates in reducing runoff, thereby competing water resources with other non-forest ecosystems outside the forest boundary, or in enhancing precipitation for the benefit of improved local ecosystem productivity. Recent studies demonstrated divergent hydrological responses to large-scale afforestation and vegetation greening in China, such that in the Southwest China there has occurred large water deficiency (Li et al. 2018). Revegetation in China's Loess Plateau has been cautioned for sustainable water resource limits (Feng et al. 2016). Research findings in China's Songnen Plain show that poplar afforestation has resulted in soil water shortage compared with adjacent regions (Wu et al. 2019).

In search of literature, most studies on forest water relations are concerned with stand level or regional scale evapotranspiration, and on matters of rainfall distributions in relation to forest type and structures. Examination of the implications of varying forest stands to catchment and watershed hydrological processes is almost an impossible task due to discrepancies in forest distribution in relation to landscape features and the complexity of waterflow movement and distribution. Unlike forest carbon sequestration, which can be effectively quantified by direct measurements at stand level and scaled up by remote sensing and modelling approaches (e.g. Law et al. 2004), quantification of forest hydrological processes at the stand level and scaling up to watershed scale by modelling requires the support of assumption-based parameterization and thus produces unquantifiable uncertainties (Ouyang et al. 2014).

Linking carbon sequestration to water conservation in forestry research: a way forward

While reviews of literature show that rich information are available for understanding forest carbon sequestration from local to global scales, relatively far less are known on hydrological regulations of forests and the impacts of afforestation on regional water resources. Existing studies of forest carbon sequestration and hydrological regulations mostly operate on different spatiotemporal scales and deploy different methodology and techniques, making the assessment of the trade-offs between forest carbon sequestration and water conservation a highly challenging task and fraught with great uncertainty. Seldomly, the dual ecosystem services of carbon sequestration and water conservation are considered in planning afforestation schemes and formulating management strategies of natural forest protection. It largely remains an open question the effective scale that forests are operated in achieving economical carbon benefit while maintaining the water regulation functionality of regional implications.

Traditional forest planning and management are largely focused on provisioning of wood products, in which trees are harvested at intervals and the risk of overconsumption of local water resources is largely removed during re-establishment and early development. Current demand for forest carbon sequestration services and biodiversity conservation calls for full forest protection and expanded planting, putting pressure on supply of water to various other usage by natural and social demands. Apart from land availability for afforestation among different land uses, allocation of water resources would be an important criterion in designing afforestation scheme.

There are many issues yet to be resolved by carefully developed research works. For the top-down planning of afforestation in regions where water availability is anticipated to be problematic, there comes the questions of how much and where to plant trees for given land availability, known environmental implications, and sustained regional development and livelihood. For local management considerations, the questions of what trees to plant and how to plant them prevail. Solution to the issues involves research support, consideration of socioeconomic preference, mechanism of eco-compensation or payment for ecosystem services (PESs), site selection and preparation, self-sustainability; of the established forests, tending and end uses of the planted trees, etc. To address these complex questions and issues, the existing studies and knowledge with narrowly focused scopes and objectives are insufficient. In view of the trend and societal perspective on forests, we propose an integrative research framework with dual consideration of forest carbon sequestration and water conservation, as illustrated in Fig. 2. The framework builds on collaborative research among the disciplines of forest regeneration, harvesting, and protection with unified experimental design and establishment of a global or regional forest research network. The central goal of the framework is to facilitate the establishment and management of planted forests for the social wellbeing and safeguarding biosecurity, aiming for delivery of balanced forest ecosystem services in carbon sequestration, water conservation, and other social values. Such an effort can help understand the scales that the ecosystem services of carbon sequestration and water cosocialnservation could be compromised under given climatic and geographical conditions.

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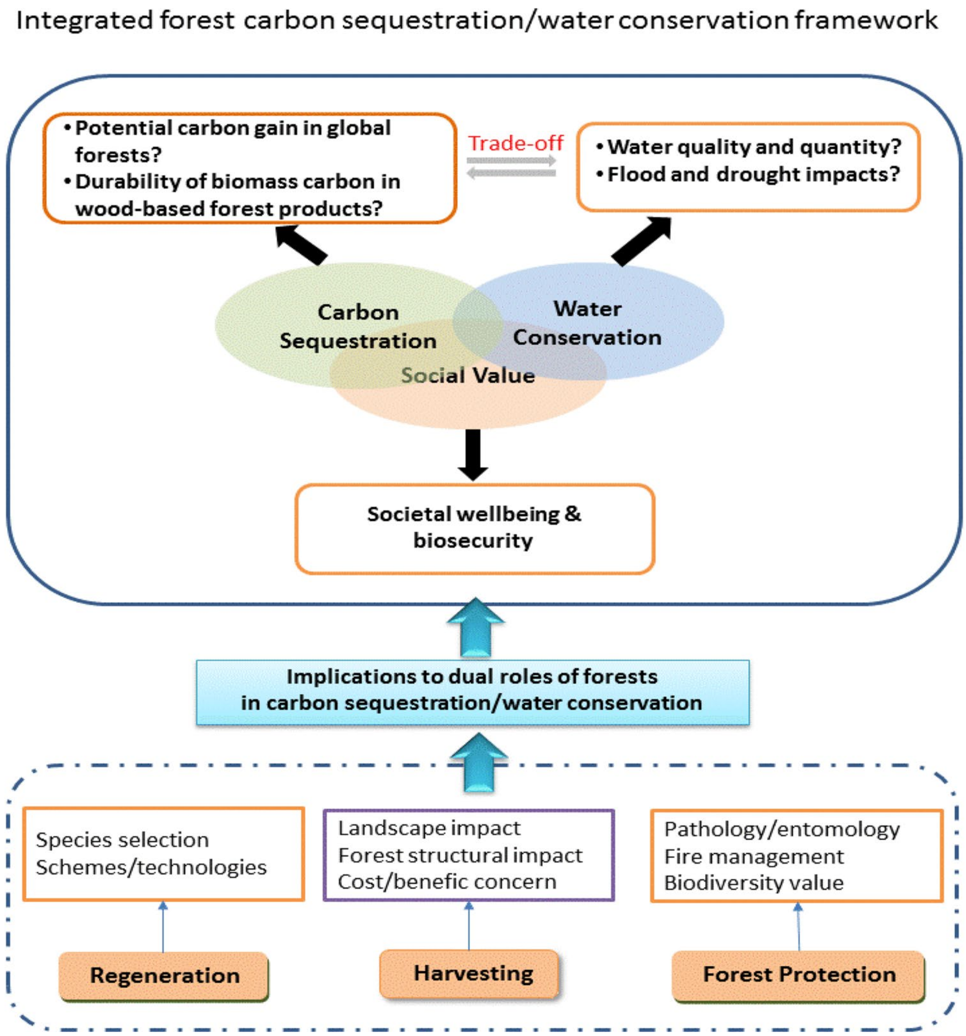

Fig. 2 Scope of research supporting development of integrated forest carbon sequestration/water conservation framework

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